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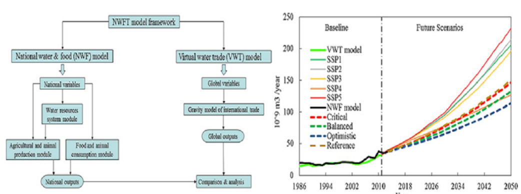
HIGHLIGHTS

- Virtual water trade should be considered when managing national water resources.
- Non-water based solutions can remediate water problems in water-scarce countries.
- Egypt's water and food gaps are projected to aggressively widen in the future.
- Both the global and national models projected similar patterns of Egypt's imports.
- NWFT modeling framework can be easily applied to any country in the world.

GRAPHICAL ABSTRACT



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ABSTRACT

This paper introduces a modeling framework for the analysis of real and virtual water flows at national scale. The framework has two components: (1) a national water model that simulates agricultural, industrial and municipal water uses, and available water and land resources; and (2) an international virtual water trade model that captures national virtual water exports and imports related to trade in crops and animal products. This National Water, Food & Trade (NWFT) modeling framework is applied to Egypt, a water-poor country and the world's largest importer of wheat. Egypt's food and water gaps and the country's food (virtual water) imports are estimated over a baseline period (1986–2013) and projected up to 2050 based on four scenarios. Egypt's food and water gaps are growing rapidly as a result of steep population growth and limited water resources. The NWFT modeling framework shows the nexus of the population dynamics, water uses for different sectors, and their compounding effects on Egypt's food gap and water self-sufficiency. The sensitivity analysis reveals that for solving Egypt's water and food problem non-water-based solutions like educational, health, and awareness programs aimed at lowering population growth will be an essential addition to the traditional water resources development solution. Both the national and the global models project similar trends of Egypt's food gap. The NWFT modeling framework can be easily adapted to other nations and regions.

1. Introduction

The natural hydrological cycle and the diversity of climatic regions in the world result in an uneven distribution, spatially and temporally, of

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precipitation on land. Traditionally, societies relied on the engineering solution of constructing dams and creating artificial storage reservoirs to supply water-deficient regions with water at times of shortage. However, the engineering redistribution of water has a limited spatial impact when compared with the socioeconomic redistribution of water in its virtual form, which crosses national and continental boundaries. Water virtually embedded in products (Hoekstra et al., 2011) has its own human-induced cycle that can be seen as a socio-economic pendant to the natural hydrological cycle. People intervene on the hydrological cycle through water withdrawals from rivers, lakes and aquifers (i.e., blue water) and employing rainfall (i.e., green water) for agricultural production and other purposes. Through global trade networks (Dalin et al., 2012), virtual water flows along socioeconomic gradients, often from places of water surplus to places of shortage, sometimes reversely. Some countries even overexploit their water resources for economic gains through exports (Dalin et al., 2017). Globally, the large variability in water presence and the diversity of its use led to a global virtual water trade (VWT) network with bi-directional flows at every node – with each region being both a virtual water exporter and importer.

There is a significant body of literature on VWT (Allan, 2003; Hoekstra, 2013; Yang et al., 2006; Chapagain and Hoekstra, 2008; Hanasaki et al., 2010) and the development of VWT networks (Dalin et al., 2012; Suweis et al., 2011; Tamea et al., 2014). Most studies focused on the network structure and the variables controlling its behavior. For example, Dalin et al. (2012) found that the flows in the network can be reasonably explained with each nation's gross domestic product, mean annual rainfall, agricultural area, and population. Suweis et al. (2011) agreed with Dalin et al. (2012) regarding the importance of the gross domestic product and the annual rainfall. It was also concluded that the importing nations are expected to play an increasingly important role in the evolution of the future network dynamics. The increased connectivity of the global network highlights the risk of systemic disruptions and the resultant vulnerability of the global food supply, especially when exporting countries change to non-exporting at times of scarcity. Puma et al. (2015) suggested that this could happen in particular with regard to wheat and rice. The fact that over 80% of countries have low food self-sufficiency emphasizes the importance of investigating the VWT network and its future projections. The use of complex network theory (Barabási and Albert, 1999; Newman et al., 2006) to characterize the global VWT network has been the common approach used, along with probability distributions to describe the number and strength of trade links (Konar et al., 2011; Carr et al., 2012). While studying the VWT network, Konar et al. (2012) also distinguished the trade in blue and green water, and found that as countries attempt to increase their food export, they tend to utilize more blue water (irrigation). Tuninetti et al. (2015, 2017) noted that there is a significant spatio-temporal variability in the water footprint of major crops, which of course contributes to global water savings and losses as a result of VWT (Chapagain et al., 2006).

The gravity model of international trade, a multivariate regression approach to explain bilateral trade flows, is a common approach to explain the trade flows in a VWT network (Tamea et al., 2014). Acknowledging its potential contribution to understand the global redistribution of virtual water flows, hardly can this stand-alone global modeling approach in its current form attract potential users and policy makers at scales where decisions are typically made. In order to be beneficial, virtual water trade information needs to better align to the needs of (water) resource managers and policy makers at the national scale (El-Sadek, 2010; Wichelns, 2001), and VWT models need to be used in combination with water models typically applied at national level to inform water allocation decisions.

Numerous studies focused on VWT on the national scale. For example, Schyns and Hoekstra (2014) assessed the added value of including the analysis of VWT in a national water resources study for Morocco. Schyns et al. (2015) analyzed Jordan's water security in the light of its high domestic water scarcity and high reliance on virtual water imports. In a case study for Tunisia, Chouchane et al. (2018) analyzed VWT patterns in relation to environmental and socioeconomic factors. Mekonnen and Hoekstra (2014) assessed Kenya's water resources use and availability and how the country can mitigate its water scarcity by increasing imports of water-intensive products. Karandish and Hoekstra (2017) demonstrated the importance for national water policy formulation of considering both international and interregional VWT in a case study for Iran. Zhuo et al. (2016) developed water footprint and virtual water trade scenarios for China, considering five driving factors of change: climate, harvested crop area, technology, diet, and population. El-Gafy (2014) developed a model to estimate the water footprint of wheat produced in Egypt and crop-related VWT under different scenarios and found that water saving can be achieved as a result of VWT. Even though many studies on national VWT consider changes of water use and VWT over time, none of them combine the analysis of national water use dynamics and global trade dynamics, and this is achieved in this paper. Future scenarios of changing national VWT should be validated or put in the context of future global VWT scenarios.

Water resource management cannot be seen as something restricted to just one specific nation or river basin (Hoekstra, 2011). On the one hand, consumption of food and other products in a country usually translates to water demands elsewhere (related to imported products). On the other hand, water demand in a country that relates to producing export products, aggravates national water demand beyond what one would expect given the consumption pattern of the national population (Hoekstra and Chapagain, 2008). Thus, water resources management on national scale should consider water in its entirety, i.e. in real and virtual forms.

Water-poor countries are in pressing need to manage their water needs (real and virtual forms), which demands for an approach that goes beyond managing the nationally available water resources. The aim of this paper is to introduce a new modeling approach for the analysis and possible management of both real and virtual water at a national scale. This approach should have the ability to accommodate the notion that national water resources analysis is to be embedded in and put in the context of a global analysis of water resources availability. Therefore, it should be possible to assess the virtual water trade with the rest of the globe, and the projected changes in imports and exports under different national and global scenarios. We consider here the case of Egypt, a water-poor country, a major food importer (FAO, 2017a), and the world's largest wheat importer, to exemplify the development of a national water, food, and trade (NWFT) modeling framework. The framework includes a system dynamics model of national water-food supply and demand and a gravity model of international virtual water trade, running in parallel for analysis and comparison.

2. Virtual water trade modeling: challenges and possible solutions

Existing virtual water trade (VWT) models (e.g., Carr et al., 2013; Fracasso, 2014; Sartori and Schiavo, 2015) are mainly data driven, employing some logically governing variables (drivers) to characterize historical VWT. The VWT models capture the patterns of exports and imports. A conceptual concern regarding the models is that each virtual water flux between two nodes in the network (VWT from region i to region j) is typically estimated by two gravity models (Tamea et al., 2014): one demand-driven export model to estimate trade of country i to country j, and another supply-driven import model to estimate trade of country j from country i. Eventually, a single flux value can be estimated as the average of the two calculated values of the same flux (Tamea et al., 2014; Tuninetti et al., 2016). As a result of the approach, the models do not preserve the global food (or virtual water) balance; i.e. the sum of all regions' exports is not equal to the sum of all imports, although averaging the dual estimates improves the models' fit of the data.

In this study, we consider only one of the two estimates of the virtual water flux from node *i* to node *j*. The export model estimate was chosen, because it typically has higher R^2 values than the import model (Tamea et al., 2014). The estimated export from *i* to *j* is considered as the import of *j* from *i*. This is logically acceptable and eliminates the dual estimates issue. A food balance equation (tonne/y) can be written at each node as Eq. (1) shows:

$$\mathrm{PROD} + \mathrm{IMP} = \mathrm{EXP} + \mathrm{CONS} + \mathrm{LOSS} + \Delta\mathrm{S} \tag{1}$$

where PROD is food production, CONS food consumption, LOSS the food losses, ΔS the increase in food stocks, EXP the total food export, and IMP the total food import.

Corresponding to the previous food balance equation is the following virtual water balance equation (Hoekstra et al., 2011), which was adopted at each node of the model:

$$\mathrm{WF_P} + \mathrm{VW_{imp}} = \mathrm{VW_{exp}} + \mathrm{WF_C} + \mathrm{WF_L} + \mathrm{WF_S} \tag{2}$$

where $\mathrm{WF_P}$ represent the water footprint of national production, $\mathrm{WF_C}$ the water footprint of national consumption, $\mathrm{WF_L}$ the water footprint of food losses, $\mathrm{WF_S}$ the water footprint of stock increase, $\mathrm{VW_{imp}}$ the virtual water import and $\mathrm{VW_{exp}}$ the virtual water export (all balance components in m^3/y). The VWT model is explained in more details in Section 3 below.

3. The NWFT modeling framework and the case study

The national water, food, and trade (NWFT) modeling framework, consists of two parallel-running components (Fig. 1). The first component, the national water and food (NWF) model of Egypt, estimates (i) food production and consumption and water consumption on the basis of national variables and available water resources, and (ii) then estimates the national food and virtual water trade through food and water balances. The second component, the global virtual water trade (VWT) model, characterizes the annual virtual water trade between Egypt and the rest of the world, which is here grouped into nine regions. The following subsections provide more details on the modeling framework and background information about the case study of Egypt. The two models are not coupled, but rather running in parallel for the purpose of identifying discrepancies or issues at the global scale that might be worth attention from policy makers at the national scale.

3.1. Egypt: the growing concerns over water and food security

Egypt is the most populous country in North Africa and the Middle East, with 92 million people in January 2017 and an annual population growth rate of about 2% (CAPMS, 2017). Egypt's large desert plateau is interrupted by the Nile Valley and Delta, which forms 4% of its 1 million km^2 area (FAO, 2017a) but inhabits 95% of the country's population.

The cultivated area in Egypt, surveyed in 2015 (CAPMS, 2017), is 9.1 million feddan (3.8 million ha). The agricultural sector employed about 25% of the country's manpower in 2016 (CAPMS, 2017) and contributed 14.5% to Egypt's gross domestic product, which was estimated in 2014 to be around US$ 287,000 million (FAO, 2017a). About 97% of the cultivated land is irrigated (El-Nahrawy, 2011; FAO, 2017a). Egypt imports about 40% of its cereals and exports some vegetables, citrus, dates, rice, and cotton. The water resources system in Egypt is unique; the country's dependency on water flowing into it from Nile Basin upstream countries is almost 97% of its renewable water resources (FAO, 2017a), with internal rainfall and renewable groundwater contributing the remaining 3%. With its current renewable water resources, 630 m^3/y/capita, Egypt is already below the amount needed for being able to be food self-sufficient (Falkenmark, 1989). In 1959, Egypt and Sudan signed the Nile Waters Agreement that secures 55.5×10^9 m^3/y to flow into Egypt. This water, which sustains all forms of life in Egypt is controlled by the High Aswan Dam in southern Egypt. Fig. 2 depicts the water resources of Egypt and their uses. According to the water balance of 2010 (MWRI, 2010), the agricultural sector annually receives 4.85×10^9 m^3 of water from shallow groundwater, which is recharged from the Nile and the surface irrigation system itself, 2×10^9 m^3 from deep groundwater, and 16×10^9 m^3 from drainage water reuse. The municipal and industrial sectors have higher priority than agriculture, so they are allocated water first.

3.2. The national water-food component in the NWFT modeling framework

The national water-food (NWF) model was built using the system dynamics approach (Ford, 1999), which uses stocks, flows, interactions and feedback loops to represent system elements and their relations. System dynamics has been used in modeling integrated water resources systems (Simonovic et al., 1997; Winz et al., 2009; Hassanzadeh et al., 2016a, 2016b) because of its ability to simulate natural and socioeconomic processes in one simulation environment. In this study, Stella Architect 1.4.3 (https://www.iseesystems.com) was used as the simulation environment. The NWF model runs with an annual time step and comprises three interlinked modules: (i) crop and animal production, (ii) food consumption, and (iii) water resources system.

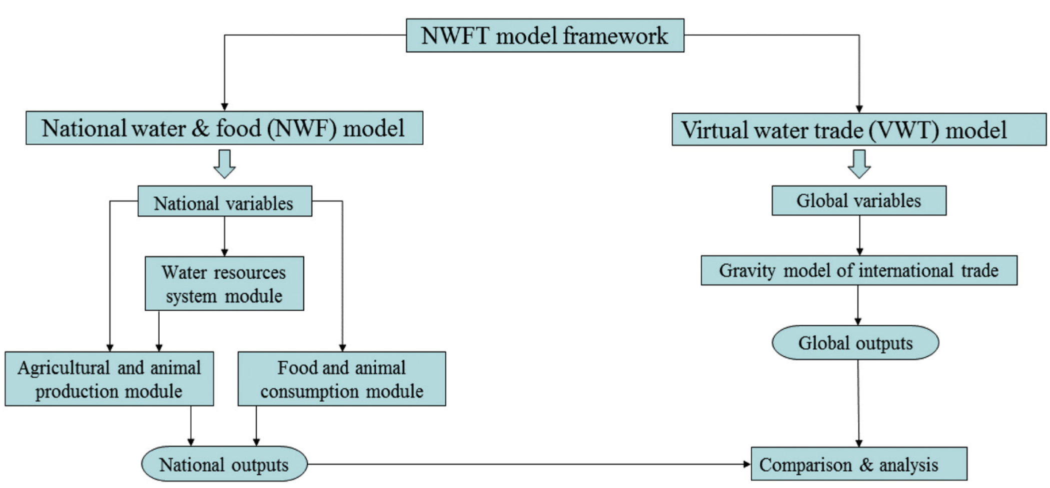

Fig. 1. Simplified schematic diagram of the NWFT modeling framework.

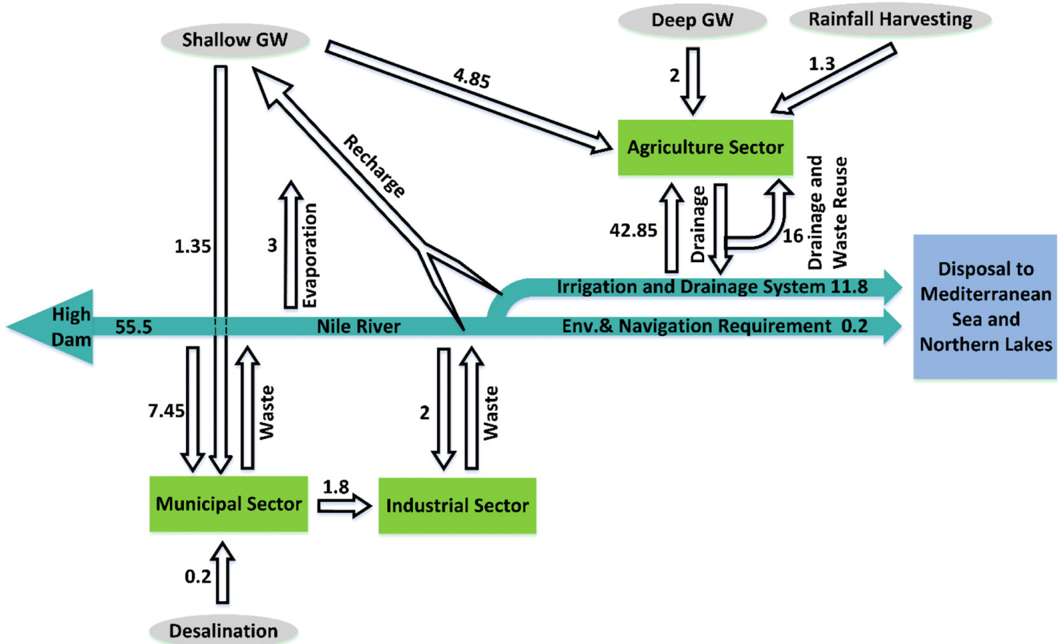

Fig. 2. Water resources system in Egypt. All numbers are in 10^9 m^3/y.
Source of data: MWRI (2010).

3.2.1. Crop and animal production module

For a total of 78 crops (72 food crops, 3 non-food crops, and 3 fodder crops), harvested areas (ha) and yields (tonne/ha) were obtained per year for the period 1986–2013 from FAO (2017b). Egypt's annual production (tonne/y) per crop was calculated by multiplying harvested area and yield. The simple productivity function from Doorenbos and Kasssam (1979) was used to modify yields under scenarios of water shortage:

$$\left(1-\frac{Y_i}{Y_{max}}\right)=k_i\left(1-\frac{CW_i}{CWR_{max}}\right) \quad (3)$$

where Y_i is the actual yield of crop i, Y_{max} is the maximum yield if the actual water available for the crop (CW_i) is equivalent to the crop water requirement (CWR_{max}), and k_i is a crop-specific yield response factor, available through FAO (2017b), representing the effect of a reduction in *water availability* on yield.

Production of animal products was calculated with a similar approach used for crop production. Animal feed is the major component that contributes to the total water footprint of animal production. In Egypt, the major feed crop is berseem (Egyptian clover), followed by concentrate feeds that are mainly composed of grains. In the NWF model, a separation was made between food and feed to prevent duplication in calculations. Annual animal feed consumed per head was estimated as in Mekonnen and Hoekstra (2012) and the water consumed to produce this feed was then estimated based on the water footprint per unit of feed crop from Mekonnen and Hoekstra (2011). In addition, animals and animal products require drinking and service water (m^3/head), which was obtained for Egypt from Chapagain and Hoekstra (2003). Crop and animal production were added to obtain Egypt's total agricultural production (tonne/y). The production of food crops and animal products were added to get national food production (tonne/y). The way this production module was built allows for investigation and scenario analysis of individual products, if such details are needed.

3.2.2. Food consumption module

The food crops and animal products considered in the consumption module of the NWF model are 81 items. This is more than those in the production module because of imported food products, which are consumed but not produced in Egypt. The consumed food mix (kg/y/capita) in Egypt was obtained from the food balance sheets by FAO (2017b). The national food consumption (kg/y) for each food item is calculated by multiplying the food consumption mix by annual population. The nutritional energy intake (kcal/day/capita) of the population is calculated by multiplying the nutritional value of each item (kcal/kg) by the amount of food consumed. This configuration allows for manipulating the food mix and consumption pattern, while keeping track of the calories intake. It was observed that the national average calories intake of the Egyptian population has been increasing with the gross domestic product and stabilized over the past few years at the level of 3400 kcal/day/capita, which is similar to that of developed countries.

Green and blue water footprints (m^3/tonne) of crops and animal products consumed and produced in Egypt were obtained from Mekonnen and Hoekstra (2011, 2012), and then used to calculate the water footprints of production and consumption (m^3/y). Surplus (production in excess of consumption) or deficit (consumption in excess of production) were calculated and assumed to be equivalent to Egypt's exports and imports, respectively. The exports and imports were calculated in terms of product trade (tonne/y) and virtual water trade (m^3/y). The modeled imports and exports were compared with FAO records of Egypt's actual imports and exports. The modules of production and consumption were configured based on Egypt's food balance sheet provided by FAO (2017b) over the historical record (1986–2013), and no calibration parameters were needed.

3.2.3. Egypt's water resources system module

The water resources system module is a national-scale water accounting and allocation model that represents the system shown in Fig. 2. The annual municipal water use was calculated based on the population and the municipal water use rate (m^3/y/capita). All desalination water, current and future expansion, is allocated to municipal water use. The municipal sector, then, receives 15% of its demand from shallow groundwater (Allam and Allam, 2007; MWRI, 2010), and the rest is supplied from the Nile. Twenty percent of the industrial water use is accounted for already within the municipal sector, and the remaining industrial needs are supplied from the Nile. Data on industrial water demand are available for the years 1990, 2000, and 2010 from Abu Zeid

(2007), Allam and Allam (2007), and MWRI (2010). Linear interpolation was used to fill the annual time series from 1986 to 2013. The consumptive use ratios of industrial and municipal water are 37% and 25% respectively (MWRI, 2010). The municipal and industrial waste water (treated and untreated) is returned back to the Nile and irrigation system, and is accounted for in the reuse of water for agriculture.

Agricultural water consumption (evapotranspiration), which was estimated to be 4700 m^3/feddan/y (feddan = 0.42 ha) as a national average, was calculated within the agricultural production module based on the crop areas of each crop and the corresponding blue water footprint. The total irrigation requirement was calculated by dividing the consumptive use of agriculture by irrigation efficiency. The amount of water needed for animal production was calculated and added to the crop irrigation water to calculate the total water supply for agriculture. The agricultural sector receives water from deep and shallow groundwater, the Nile, and drainage water reuse. The renewable shallow groundwater aquifer can provide a safe yield of 8.4×10^9 m^3/y based on the water balance in 2010 (MWRI, 2010). This safe yield was estimated every year based on the proportional change in recharge, which is affected by Nile water supplied to agriculture and the irrigation system efficiency (details are in supplemental materials Appendix A). The abstraction from the shallow groundwater for both municipal and agricultural purposes was calculated every year to ensure that it does not exceed the safe yield. The amount of agricultural drainage water is estimated based on the water supplied for irrigation and the irrigation efficiency. The total drainage water available for reuse is the summation of agricultural, municipal, and industrial return flows. The drainage reuse in 2013 was around 57% of the total drainage water. The model allows the agricultural sector to access the drainage water reuse as specified in the scenario, with a maximum of 60% of the available drainage water. The limit of 60% is set by the Egyptian MWRI to maintain a reasonable level of water quality. Around 0.2×10^9 m^3/y is secured for instream flows to allow for navigation. The unused drainage water is discharged to the northern lakes and the Mediterranean Sea to balance water salinity and substitute lake evaporation, a process which is essential for healthy aquatic system. The only variable that was marginally fine-tuned to reproduce the recorded data is the irrigation system efficiency in Egypt. The irrigation system efficiency is known to range from 44%–66% (IWMI, 2013), with improvement over time due to the improvement in irrigation methods and technologies. With minimum manual calibration, we found it to increase from 40% to 63% over the baseline period (1986–2013). More details of the water resources model are provided in the supplemental materials (Appendix A).

3.3. The trade component in the NWFT model

The main purpose of this model is to characterize the virtual water trade into and out of Egypt. Therefore, there is less emphasis on individual countries, and thus, countries were integrated into nine regions to make the model and its links smaller and more parsimonious. The country under consideration, Egypt in this study, is kept as an individual. The nine regions are: Africa (AF), Middle East and North Africa (ME), East Asia and Pacific (EA), South Asia (SA), East Europe and Central Asia (CA), Europe (EU), North America (NA), Latin America and Caribbean (LA), and Oceania and New Zealand (OC). For developing countries, we used the aggregation into macro-regions proposed by the World Bank (http://www.worldbank.org/en/where-we-work), then we added developed countries grouped into Europe, North America, and Oceania. This way, the VWT model has 90 inter node links along the entire period of 1986–2011, instead of the original thousands of links (e.g. 16,254 links in year 2011, established among 213 countries) in Tuninetti et al. (2016).

In this study, after aggregating the country level data into regions, the model became simpler with only *P*, *GDP*, and WF_P found to be influential drivers. Therefore, the gravity equation in the region-based VWT model developed in this study takes the following form:

$$VWT(i,j) = \beta_{oi} \cdot (P_j)^{\beta_{1i}} \cdot (GDP_j)^{\beta_{2i}} \cdot (WF_{P,j})^{\beta_{3i}} \tag{4}$$

where *VWT(i, j)* is the virtual water trade from region *i* to region *j*, all parameters denoted by β are related to the exporting region *i* and estimated based on the data using ordinary least squared method, applied to the logarithm of fluxes and the logarithm of drivers. Significant variables were identified with the Student's *t*-test considering a 5% significance level. The drivers are the independent variables pertaining to the importing region *j*, and as defined earlier. As described in Section 2, the flux estimated using Eq. (4) is the same as the import of region *j* from region *i*. Accordingly, the 10-regions (node) based VWT model has a total of 10 equations of the form as Eq. (4) and 40 parameters, as well as 10 equations of the form as Eq. (2). The 40 parameters were calibrated using a total of 2340 observations, namely 90 flows for each year between 1986 and 2011. Even though WF_C was not used as a driver in the gravity equation, WF_C of each region was used as shown in Eq. (2) to account for the virtual water balance and estimate the losses and stock variation for every region. The data between 1986 and 2011 were used for the VWT model because it is the time frame within which all data were available. Population and agricultural production and consumption-related data are available publicly through the FAO (2017b). The blue and green water footprint of each product (m^3/tonne) was obtained from Mekonnen and Hoekstra (2011) and multiplied by the production quantity (tonne) to calculate the water footprint of each product (m^3). The water footprint of all food produced and consumed were summed up, then divided by the population to calculate WF_P and WF_C, respectively. The *GDP* data were obtained from the UN (2017). The VWT model was developed and evaluated based on the baseline period (1986–2011), then it was used to project the future VWT up to 2050 using the future socioeconomic shared pathways (SSPs). Details of developing the future projections and the SSPs are provided in Section 4.

4. National and global scenarios

The proposed NWFT modeling framework is not intended to do forecasting, but rather to allow the investigation of the water-food nexus at the national level, assessment of the influential variables and impacts of policy decisions, and analysis of potential scenarios for future projections at the national and global levels, along with the change that they might cause relative to the baseline conditions. For this purpose, scenarios of future projections at both the global and national level of Egypt were generated and analyzed.

4.1. National scenarios

Egypt's Ministry of Water Resources and Irrigation (MWRI, 2010) developed three future scenarios, *Critical, Balanced, and Optimistic*, regarding water resources supply and demand in Egypt till 2050. The scenarios consider various water and socioeconomic combinations in their formulation. Variables considered are: (1) possible increase in Nile water inflow from projects of water saving in upstream countries, (2) different levels of internal water resources development of shallow and deep groundwater, reuse of drainage water, desalination, rainfall harvesting, and evaporation losses from the surface irrigation system, (3) socioeconomic variables, such as population and industrial growth, and (4) policy variables, such as agricultural land expansion and municipal water use reduction. In this study, a *Reference* scenario was added, which represents business as usual, with no significant changes relative to the past trends. The details of the four scenarios are provided in Table 1.

MWRI's scenarios do not assume changes in land productivity, and do not include the food consumption pattern. These two variables

Table 1
Potential scenarios of Egypt's water supply and demand (2013–2050).

Driver	Reference[a]	Critical	Balanced	Optimistic	Uncertainty range
Annual population growth rate	2%	2%	1.8%	1.65%	±10%
Food consumption pattern	Unchanged	Unchanged	Increase in veg. & fruits (20%) and meat (26%), decrease in cereals (4%)	Increase in veg. & fruits (20%) and decrease in cereals (2.6%)	Unchanged
Increase in available water resources over the period 2013–2050 (10^9 m^3/y)[a]	**+2.42**	**+6.82**	**+4.22**	**+4.22**	
	Nile flow + 0	Nile flow + 0	Nile flow + 2	Nile flow + 4	±5%
	Shallow GW + 1.9	Shallow GW + 1.9	Shallow GW + 1.1	Shallow GW + 1.1	±10%
	Deep GW + 0	Deep GW + 1.63	Deep GW + 1.63	Deep GW + 1.63	±20%
	Reuse +0	Reuse +2	Reuse −2.3	Reuse −4.8	±20%
	Desalination + 0	Desalination + 0.77	Desalination + 1.27	Desalination + 1.77	±50%
	Rain harvesting + 0.02	Rain harvesting + 0.02	Rain harvesting + 0.02	Rain harvesting + 0.02	±30%
	Evaporation + 0.5	Evaporation + 0.5	Evaporation + 0.5	Evaporation + 0.5	±20%
Municipal water demand (m^3/y/capita)[a]	From 114 in 2013 to 79 by 2050	From 114 in 2013 to 79 by 2050	From 114 in 2013 to 82 by 2050	From 114 in 2013 to 82 by 2050	0% to −50% (114 to 57)
Annual growth in industrial water use (%)	0%	0.65%	1%	1.35%	±50%
Agriculture water consumption (m^3/Feddan)	4700 (unchanged)	From 4700 to 4500	From 4700 to 4400	From 4700 to 4300	±5%
Irrigation efficiency	63% (unchanged)	From 63% to 65%	From 63% to 70%	From 63% to 75%	±10%
Agriculture expansion (million Feddan)	No increase	Increase to 10	Increase to 10.8	Increase to 11.8	±20% for the target
Land productivity (tonne/Feddan)	Unchanged	Unchanged	Unchanged	Unchanged	±20%
Annual animal growth rate	Unchanged	Unchanged	Increased to match increase in consumption	Unchanged	±20%

Feddan = 0.42 ha.
[a] Some inevitable and expected changes were considered in the Reference scenario as they are currently happening.

were added to complete the scenarios. The changes specified by the MWRI were used in all categories, and we did not change the land productivity except for uncertainty analysis. For both the Critical and Reference scenarios, the food consumption pattern was not changed. However, in the Balanced scenario, we increased meat consumption by 26% to match the expected behavior with the economic growth (Alexandratos and Bruinsma, 2012), which led to a 4% decrease in cereals to keep the nutritional energy intake at about the same current level. For the Optimistic scenario, we tried to reflect also optimism in the consumption pattern by keeping the meat consumption unchanged, while increasing the consumption of vegetables and fruits by 20%, which led to 3% decrease in cereals consumption.

For such a complex water-food nexus at a national scale, it is important for policy makers to understand the influential variables in the system. For this purpose, sensitivity analysis (SA) was conducted with the most important variables that affect the production, consumption, and water resources modules. The Reference scenario was used in this analysis to measure the relative change as a result of variable perturbation. We used the system dynamics concept of *reference mode* that is perceived to be a representative index, in the form of a time series, of the system performance (Ford, 1999). Either of the food (or water) gap or food (or water) self-sufficiency can be used for this analysis. Even though scenarios represent probable realistic future conditions guided by historical trends and data, SA quantifies the influence of major variables by perturbing their values (Table 2) beyond the ranges of the various scenarios, so the consequences of more acute policies are tested. For example, the Nile water inflows to Egypt were changed in the range of $\pm 10 \times 10^9$ m^3/y. The SA was conducted by perturbing one model variable (or a group of variables) at a time while maintaining the other variables unchanged.

Table 2
Sensitivity analysis ranges used with Egypt's NWF model.

Model component	Variable	2013 value	SA range
Production	Agriculture area (million Feddan)	9.2	9.2 to 15
	Nile water (10^9 m^3/y)	55.5	45.5 to 65.5
Consumption	Annual population growth (%)	2.0	2.0 to 0.5
Water resources	Desalination (10^9 m^3/y)	0.23	0.23 to 4.0
	Deep groundwater (10^9 m^3/y)	2.36	2.36 to 4.0
	Irrigation efficiency (%)	63	63 to 80
	Municipal network efficiency (%)	70	70 to 90
	Municipal water use (m^3/y/capita)	114	114 to 57

Feddan = 0.42 ha.

Uncertainty analysis (UA) was also conducted with the NWF component to reflect the uncertainties in the various variable values in the four investigated scenarios. UA is different from the SA in two aspects; first, the ranges of uncertainty (Table 1) were kept limited and realistic to reflect best estimates of uncertainty. For example, only 5% uncertainty was considered regarding the Nile water flows in each scenario ($\pm 2.75 \times 10^9$ m^3/y) as this is in the range of the typical variability in the annual flows released from the High Aswan Dam. Desalination plans and industrial growth in Egypt are highly uncertain as the country may be far from the scenario ranges in either sides, especially in light of the recent significant socioeconomic and political changes. Therefore, the range was increased to ±50%. The second difference between SA and UA is that in UA, all variables were perturbed simultaneously (all at a time) to reflect the reality of uncertainty. The Latin Hypercube sampling approach built in Stella Architect was used to sample values from all variables in 1000 runs.

4.2. Global scenarios

The climate change research community developed five scenarios of global societal development, called the shared socioeconomic pathways (SSPs) (O'Neill et al., 2017). These SSPs consider changes in demographics, economy and lifestyle, policies, technology, natural resources, and human development for distinguishing the five scenarios.

IIASA (2016) provides the population, gross domestic product and urbanization data of all SSPs for all countries for the period of 2000–2100. Data on population (P) and gross domestic product (GDP) were extracted for all countries up to year 2050 and processed to match the ten world regions distinguished in this study. The future values of water footprint of agricultural production (WF_P) are unknown for each region. These values depend on many factors that vary by region, like the water resources availability, the agriculture policy and management decisions, and the degree of development and technology (Ercin and Hoekstra, 2014; Jin et al., 2016). So, an ideal way to estimate WF_P is to develop a model like NWF for every country in the world and simulate the future values based on assumptions for the controlling factors, which is considered beyond the scope of this study. Instead, two different experiments were adopted. In Experiment I, data on WF_P per region (expressed in m^3/y/capita) at the end of the baseline period (2011) were assumed to remain constant up to the year 2050. This implies that each region attempts to keep the food production per capita at the level of 2011, assuming that the water footprint of production in every region keeps pace with regional population growth. In Experiment II, even if resources availability is not a problem for some regions (Shiklomanov, 2000), other factors like water quality and socio-economic factors (Simonovic, 2002; Duchin and López-Morales, 2012) might make them fail to maintain 2011 levels of per capita food production. Hence, some other regions would increase their per capita food production over 2011 levels to trade more food. In this experiment the per capita WF_p is assumed to be varying, for some regions it will increase while decrease for others. Iterations were needed to solve Eqs. (2) and (4) in the trade model using the IIASA's P and GDP data and by assuming no significant change to food waste per capita compared to 2011 levels (Kummu et al., 2012). The annual WF_P series up to 2050 were generated for all SSPs in the ten regions and can be found in the supplemental materials (Appendix B). Finally, the VWT model was used to generate the virtual water (food) imports of Egypt till year 2050 under the five SSPs.

5. Results and analysis

5.1. National water-food model results

NWF model simulates Egypt's food production and consumption and its food and water gaps for the baseline period 1986–2013 and the future up to 2050. In all scenarios, the increase of food production is projected to be slower than that of the baseline period due to the limitation of fresh water availability (see Fig. 3). Agricultural production has been increased in the past due to the increase of agriculture land and improvements in crop yield (tonne/ha), at the same time, Egypt maximized its reuse of drainage water and improved irrigation efficiency. Interestingly, MWRI's Balanced and Optimistic scenarios are not significantly different with regard to food production (Fig. 3a). However, when the national food consumption (Fig. 3b) is taken into consideration, the Optimistic scenario becomes obviously better with regard to the national food gap (Fig. 3c). The Optimistic scenario is projected to have a 25 million tonne smaller food gap compared to the Balanced scenario. Even though the Balanced scenario projects higher food production than the Critical scenario, it was set off by the projected increase in meat production and consumption, which consumed water that would have been otherwise used for crop production. This is an important effect of food consumption behavior on the food and water gaps. The food gap translates into a water gap (Fig. 3d), based on the internal water footprint of each crop and animal product. Under all scenarios, Egypt's food and water gaps are projected to widen with rates higher than those of the baseline period. This occurs because the negative effect of the low rate of production increase is exacerbated by the high rates of national food and water consumption increase due to the high population growth.

As the municipal and industrial water uses have higher water allocation priorities than agriculture, the demand growth in municipal and industrial sectors affects the water available for agriculture and food production. Fig. 4 shows the total water resources supplied and the percentage of water use (allocation) for each sector under the Balanced scenario (detailed water uses for different scenarios are provided in the supplemental materials, Appendix D). The increase in water resources supplied between 1986 and 2013 is mainly due to the expansion in water reuse and groundwater extraction. Such increase in the future is limited because very small potential for expansion exists. The sectoral shares in total water use change over time: municipal and industrial water use increase their percentage of usage at the cost of agriculture, which has almost a fixed allocation of 67×10^9 m^3/y between 2013 and 2050. Taking year 2013 as a reference, an annual growth rate in Egypt's population of 2% leads to 2% (187 million m^3) increase in municipal water use, 2% (1.9 million tonne) increase in food consumption, and thus, 7.1% (1.5 million tonne) increase in the national food gap.

While Egypt is a major food importer, the country also exports some agricultural products (Fig. 5). Egypt's food exports are small compared to the food imports (Fig. 3), with total exports amounting to 20% of the imports. The NWF model shows a slightly lower accuracy in modeling the exports, which does not affect the overall balance due to their

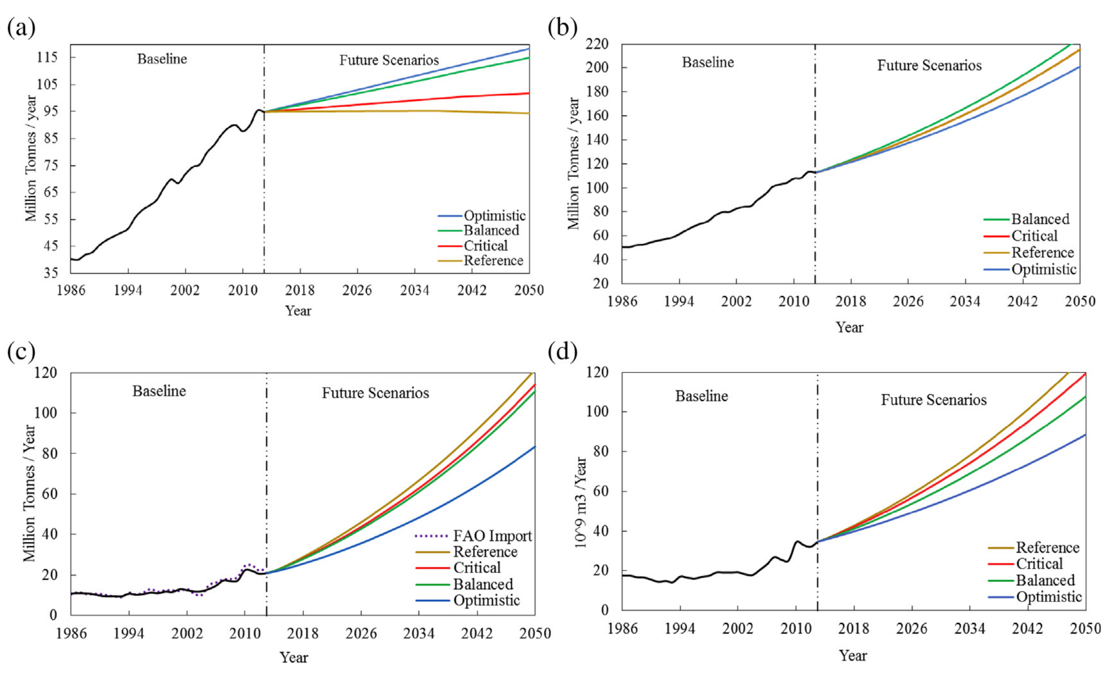

Fig. 3. Egypt's baseline and projected (a) national food production, (b) total domestic food supply (national food consumption), (c) national food gap (imports), and (d) national water gap.

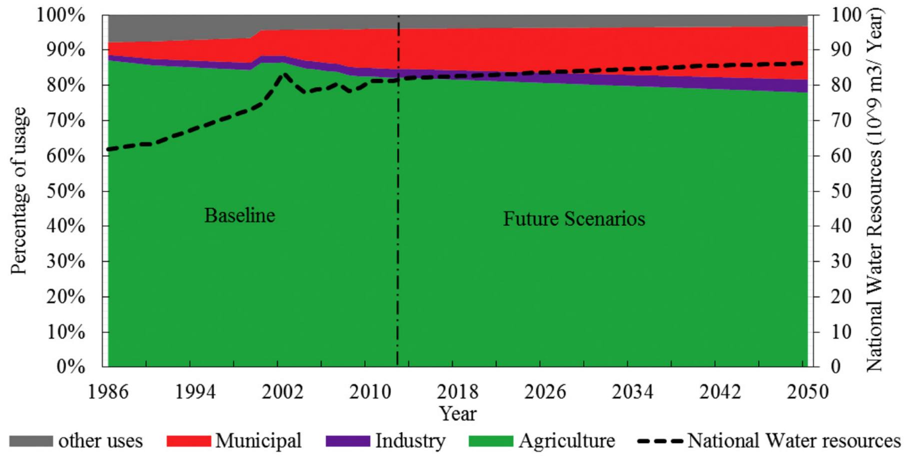

Fig. 4. National water resources supplied and the progression of the percentages of usage by different sectors in baseline and future Balanced scenario.

small values. The evolution of the national food and water gaps over time in Egypt can be quantified and visualized using the self-sufficiency index (Fig. 6). Self-sufficiency is the amount of the resource available domestically divided by the total need or consumption. The current food self-sufficiency (tonne/tonne) of 80% is projected to decrease to a level between 45 and 59% by year 2050. The corresponding values of Egypt's water self-sufficiency are 70% (currently), decreasing to a range of 40–50%. The low values of the projected food and water self-sufficiency in Egypt, mainly due to its limited water resources compared to its population needs, explain the nation's sensitivity to any dispute over Egypt's share of the Nile water and its sustainability.

5.1.1. Sensitivity analysis

Increasing the mean annual Nile water by 10×10^9 m^3/y (a number stretched beyond the MWRI's Optimistic scenario) reduces Egypt's food gap from 121 to 106 million tonne in 2050 (Fig. 7), provided that all other variables are kept unchanged. Such increase in the external water resources of Egypt is estimated to require an investment of around US$ 10,000 million (MWRI, 2017). A similar effect is achievable by a combination of policy instruments and developments of Egypt's internal water resources, by decreasing the municipal water use from 114 to 80 m^3/y/capita, increasing the municipal water distribution network efficiency from 70% to 82%, increasing the overall irrigation system efficiency from 62% to 73%, increasing the deep groundwater use from 2.36 to 3.4×10^9 m^3/y, and enlarging the desalination capacity from 0.23 to 2.5×10^9 m^3/y (Fig. 7). The required capital investment for such combination of measures is around US$7700 million (MWRI, 2017). However, internal water resources developments entail significant amounts of annual operating cost and energy use, especially for desalination, deep groundwater use and the newer irrigation systems. Such investments, which are approximately 10–15% of Egypt's annual budget, will reduce Egypt's food gap in 2050 by only 12%. This reflects the severity of Egypt's water resources problem.

As noted earlier, and shown in Fig. 7, population growth has a dramatic effect on Egypt's food and water gaps. The 15 million tonne reduction in the food gap in 2050 can be achieved by lowering the population growth rate from 2.0% to 1.79%. Fig. 7 shows the extreme case of lowering Egypt's annual population growth to the current level of some European nations (0.5%), and its huge impact on the national food gap. This is a strong indication that investment in educational, health, and awareness programs for lowering the population growth rate can be a major part of the solution of Egypt's severe water problems. Population growth consumes water for drinking, which leaves less water available for agriculture. Population growth has thus a compound effect on the food gap: it increases food consumption and decreases food production. The above quantitative example supports the growing

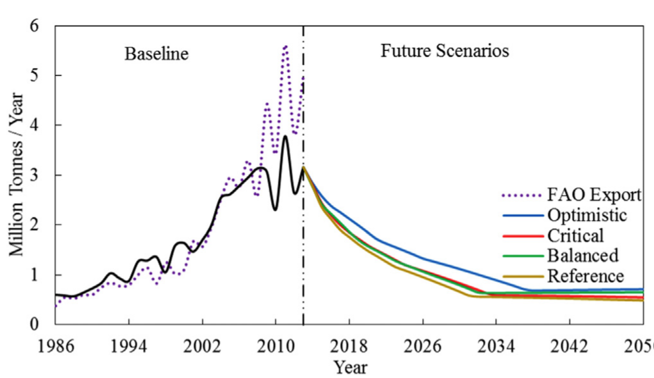

Fig. 5. The food exports from Egypt over the baseline period and projected for the future under various national scenarios.

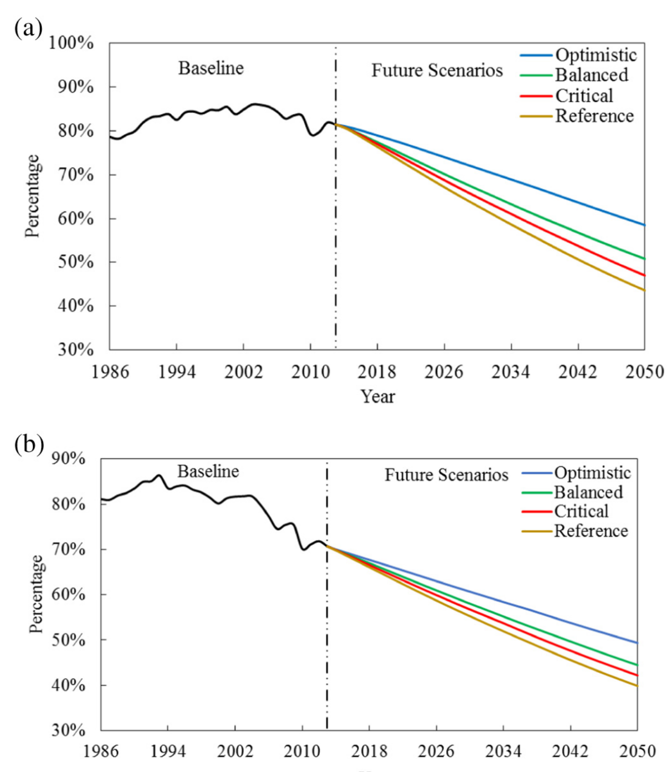

Fig. 6. Egypt's (a) food self-sufficiency, and (b) water self-sufficiency.

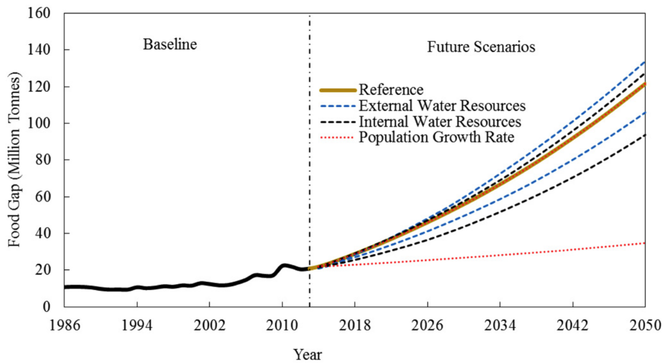

Fig. 7. The sensitivity of Egypt's food gap to: external water resources (Nile water), internal water resources development, and the population growth rate.

realization that addressing water resources problems may not be through a water-based solution. Other figures and results of the sensitivity analysis with regard to the individual variables are provided in the supplemental file (Appendix E). IIASA's various SSPs project lower population growth of Egypt up to year 2050. For this reason, we include also in Appendix F the projected food gap of Egypt based on IIASA's population projections. However, three of the SSPs, for example, project Egypt's population to reach 102 million in 2030, when this number is projected to be achieved before 2020 by the local authorities (CAPMS, 2017).

5.1.2. Uncertainty analysis

Fig. 8 depicts a summary of the uncertainty analysis of the NWF model, using the food gap (million tonne) as the performance index. Results are available throughout the simulation period (2014–2050), however, three years were selected for the analysis: the first year of the projection into the future (2014), 2030, and 2050. In 2030, the uncertainty range is reasonable with standard deviation values are in the range of 3.9 to 5.5 million tonne for the four scenarios. Because of the differences in the mean value, the coefficient of variation (CV) is a better measure. Both the Reference and Critical scenarios have CV values of 0.06 and 0.07, respectively. This uncertainty increases to 0.11 for the Balanced scenario. The uncertainty increase in the Balanced scenario is attributed to the increase in animal stock that was considered to supply the increase in meat consumption. Increasing meat production places a high demand on water resources, which affects the water available for agriculture. Obviously, the uncertainty is growing over time as we look further into the future. Moving from 2030 to 2050, the uncertainty, quantified by CV, increases in the range of 30% to 43% relative to 2030, with the maximum increase in uncertainty in the "meat" scenario. Considering the mean (or median) values of all scenarios, one can easily rank them with regard to the resulting food gap, with the Optimistic scenario leading to the best results for Egypt. However, the uncertainty ranges show that the four scenarios are overlapping and their results may not be much different from one another, especially in the near future (2030).

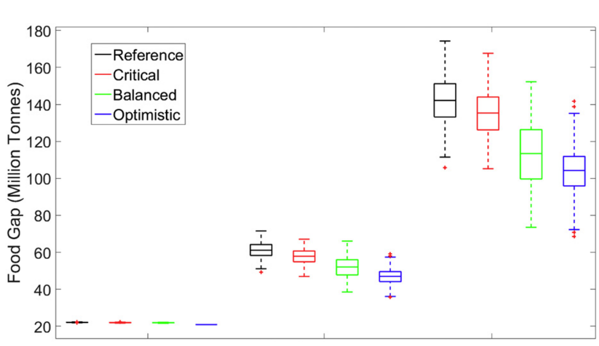

Fig. 8. The evolution of Egypt's food gap over time and its uncertainty under the various scenarios.

5.2. Global virtual water trade model results

For the baseline period 1986–2011, the predicted food imports of Egypt, converted into virtual water units, are shown in Fig. 9 along with the actual imports reported by FAO (2017b). The FAO reports exports and imports of food in million tonne and we converted the values into billion cubic meters of water by multiplying the food imports by the water footprint of producing the same food in Egypt. The global virtual water trade (VWT) model shows acceptable performance in capturing the pattern of the global trade with an overall adjusted R^2 value of 0.79. Even when a two third-one third split sample was tested to conduct a traditional calibration-validation with the model, a satisfactory performance was still achieved with a validation R^2 value of 0.68. However, due to the limited length of the available data, the model developed with the entire dataset of 26 years was used in this study.

The VWT model was fed with the IIASA's SSPs to project Egypt's imports till 2050. In experiment I, when the WF_P (m^3/capita) was kept constant in the future in all regions, Egypt's virtual water import increased to 76 up to 135 × 10^9 m^3/y by 2050, with an average value of 103 × 10^9 m^3/y (Fig. 10a). This constant future value of WF_P implies a significant increase in Egypt's production over the years to match the pace of population growth, and thus, imports can be kept to the lowest possible level. However, this future scenario may not be realistic as the VWT model generated unrealistically high or low waste and stock variations to keep the global food balance between exporting and importing regions. The results are provided in the supplemental file (Appendix B).

In experiment II, the generated WF_P values (m^3/capita) increased in certain regions (e.g. Eastern Europe and North America) and decreased in others (e.g. Middle East and South Asia) in the future, and we find this to be more realistic. The advancement in technology and the differences in population growth rates among the world's regions support the varying WF_P values. The new projections of Egypt's imports are shown in Fig. 10b. The imports range from 127 to 232 × 10^9 m^3/y by 2050 with an average value of 195 × 10^9 m^3/y in 2050. We also find the projections to be reasonable as the lowest imports projections of Egypt, in other words exports to Egypt from the other nine regions, happen in SSP3 and SSP4, characterized by global fragmentation and inequality where policies are oriented towards security, including barriers to trade (Fujimori et al., 2017; Calvin et al., 2017). On the other hand, the highest imports are found for SSP5, the conventional development scenario that is characterized by conventional development towards economic growth, and policies geared towards redundancy to minimize disruption (Kriegler et al., 2017). Egypt's virtual water imports are projected to increase from all regions, but the most significant increases occurred

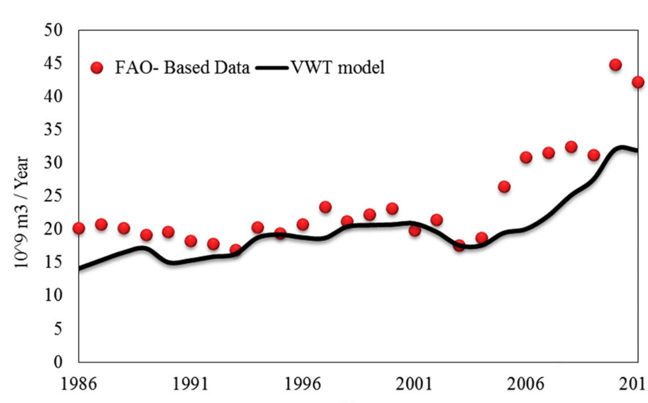

Fig. 9. Actual and modeled food imports of Egypt, converted to water units (virtual water), during the baseline period (1986–2011).

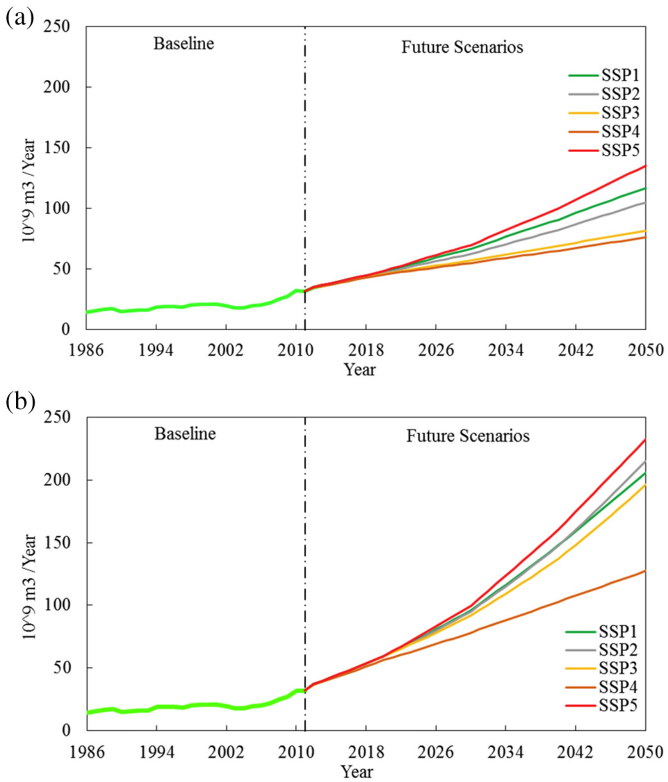

Fig. 10. The baseline and projected future virtual water imports of Egypt under the five SSPs, (a) Experiment I: constant WF_P in the future and (b) Experiment II: varying WF_P values based on stabilized food waste in the future.

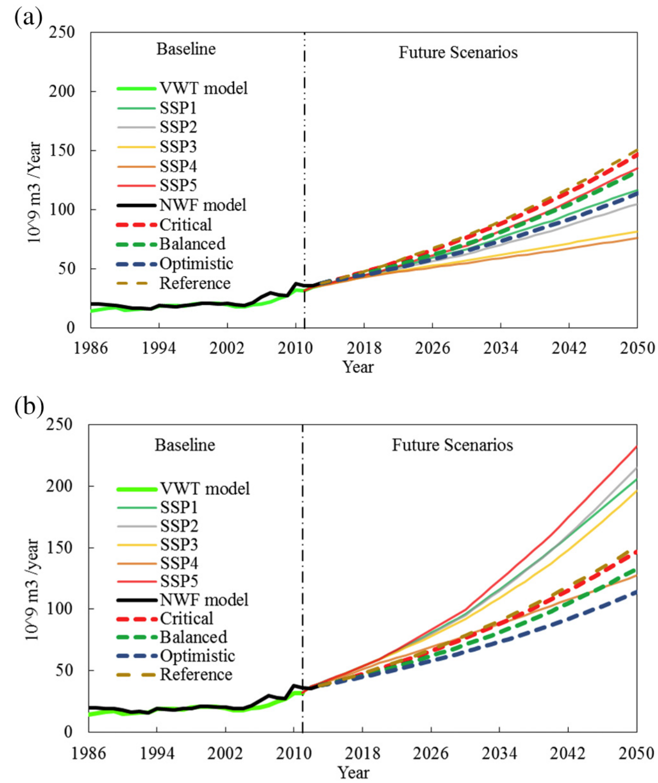

Fig. 11. Virtual water (food) imports of Egypt over the baseline period and the projected future under various national and global scenarios, (a) Experiment I: constant WF_P values in the future and (b) Experiment II: varying WF_P values based on stabilized food waste in the future.

from Africa, Latin America, and East Europe and central Asia regions (detailed tables can be found in the supplemental materials Appendix C).

6. Discussion

The general pattern and trend of Egypt's food imports projected by both the global and national models in the NWFT modeling framework are consistent, which is encouraging and supporting the credibility of both models (Fig. 11). However, taking into consideration an average value of the five SSPs, the VWT model estimates Egypt's food import in year 2050 to be 150 million tonne, which is 39% higher than the average estimate resulting from the national model (averaging the four national scenarios). SSP4 provides a close estimate to the national model, with an estimated food import in 2050 that is 8% lower than the average of the national scenarios. Ideally, developing a national model for each country, similar to Egypt's model, to estimate national surplus and shortage of each country, taking into account the national socioeconomic and development plans, and reiterating to maintain a global balance is probably the best way to project future global virtual water trade. For the purpose of this study, and for the practical use of a country like Egypt, it is useful and important to ensure that the national 2050 strategy and its associated future scenarios can be made possible from a global perspective, which can be assessed using the VWT model to a reasonable level. If Experiment I (Fig. 11a) provides the realistic global picture, it means that some of Egypt's projected future food needs are far beyond what is anticipated based on the global food availability and trade network. In this case, it is an alarming situation that requires introducing serious policy instruments that can change Egypt's food gap.

The NWFT modeling framework presented in this study has a few limitations that are worth further improvements in future studies. First, the VWT model needs to be improved, either through using the country-based model, rather than the nine-region model, or through adding more conceptual components. The food production, water use, and food consumption components need to be captured with finer levels of details in each region. Second, the NWF model can benefit from more including more socioeconomic factors, like for instance food prices. Explicit accounting of the food prices, which might affect the national consumption both in pattern and quantity, can affect the country's imports, which in turn can affect prices and add another feedback loop in the consumption modeling component. It is challenging to capture this behavior based on historical data when more than 75% of the population enrolled in food subsidy program and acquired food at non-market prices. Third, the future dynamics of water uses and supply might alter water quality, which could have impacts on the aquatic system of the Nile and Delta, and might be worth investigation in more detail.

Third, the NWF model of Egypt's water-food nexus can be extended to include energy. Currently, because of the limited contribution of hydropower and the small amounts of cooling water for thermal power, relative to other water uses, and the negligible use of Egyptian crops in bioenergy, the energy role in the nexus is limited. Nonetheless, there is a considerable input of energy in water and food supply, mainly due to the use of fertilizers and machinery in agriculture and pumping systems in irrigation and water extraction (El Gafy et al., 2017). Also, an increase in desalination can enhance the need to include energy, and study the trade-offs of its uses in industry, agriculture, and drinking water.

7. Conclusions

Virtual water traded internationally in the form of food, and other products, makes water a global resource; national water analysis and management should not only address the (real) water resources within the country, but import and export of water in virtual form as well. The

NWFT modeling framework developed in this study can be instrumental for this purpose. The water-food nexus in Egypt was captured and modeled in this study in a system dynamics simulation environment. A set of future scenarios of Egypt's water and socioeconomic conditions up to the year 2050 were evaluated using the national water-food (NWF) model, and they all revealed that Egypt is facing the challenge of widening food and water gaps. However, there are scenarios that were assessed to be more optimistic than others, and those ones require investments to develop some internal water resources through desalination, the use of fossil groundwater, improving irrigation and municipal water efficiency, lowering the population growth rate, and securing additional amounts of the Nile water flowing from upstream countries. The sensitivity analysis revealed that the exceptionally high population growth rate in Egypt plays a critical role in pushing the national water and food gaps to alarming levels.

The global virtual water trade (VWT) model, executed in parallel to the NWF model, considered the world countries aggregated into nine regions, while keeping Egypt as an explicit node. Egypt's imports of virtual water (food) were projected, up to 2050 under five different scenarios based on the socioeconomic shared pathways (SSPs). Both the global and national models projected similar patterns of Egypt's future food imports, which in turn represent Egypt's food and water gap. The similarity in the projected patterns of both models is a good indication of the validity of both the national and the global models. The NWFT modeling framework can be easily adapted to other countries and also to expand the nexus to other sectors, such as energy. This framework can be slightly modified to be applied to regional study areas rather than single nation, so it can assist decision making at different levels. The approach of analyzing water in its real and virtual forms, rather than only one of them, can be a useful approach to quantify the water-food (and perhaps energy) nexus and bridge an important gap between water resource managers and policy makers at the national level. Furthermore, the study also provides a way for policy makers at national scale to benefit from the emerging research in global virtual water trade.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2018.05.197.

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